EVALUATION OF THE ACCURACY OF 2D DETECTOR ARRAY SYSTEM FOR PATIENT-SPECIFIC QUALITY ASSURANCE (PSQA) IN ADVANCED RADIOTHERAPY

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by

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LIST OF ABBREVIATIONS

2D	Two-dimensional
3D	Three-dimensional
4D	Four-dimensional
AAPM	American Association of Physicists in Medicine
CT	Computed Tomography
DVH	Dose-Volume Histogram
HN	Head and Neck
IAEA	International Atomic Energy Agency
IC	Ionisation Chamber
ICRU	International Commission on Radiation Units
IMRT	Intensity-Modulated Radiotherapy
LINAC	Linear Accelerator
MC	Monte Carlo
MLC	Multileaf Collimator
MU	Monitor Unit
OAR	Organ at Risk
PSQA	Patient-Specific Quality Assurance
PTV	Planning Target Volume
QA	Quality Assurance
SBRT	Stereotactic Body Radiotherapy
SRS	Stereotactic Radiosurgery
TG	Task Group
TPS	Treatment Planning System
VMAT	Volumetric-Modulated Radiotherapy

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PENILAIAN KETEPATAN TATASUSUNAN PENGESAN 2D UNTUK JAMINAN KUALITI KHUSUS PESAKIT (PSQA) DALAM RADIOTERAPI TERMAJU

ABSTRAK

Teknik radioterapi termaju, seperti radioterapi termodulasi volumetrik menyampaikan dos yang menyebentukkan kepada tumor sambil mengehadkan dos kepada organ berisiko. Jaminan mutu khusus pesakit memainkan peranan penting dalam mengesahkan ketepatan penyampaian rancangan rawatan. Namun, kerumitan rancangan yang sangat menyebentuk boleh menyebabkan kadar perlepasan gama yang lebih rendah dan ralat dosimetrik yang lebih tinggi, terutamanya untuk organ berisiko bersaiz kecil. Kajian ini menilai ketepatan pengesan 2-dimensi (2D), PTW Octavius 1500 untuk jaminan mutu khusus pesakit dalam radioterapi dengan membandingkan keputusannya dengan ukuran dos mutlak dan data log. Ketepatan dos dinilai melalui perbandingan antara ukuran pengesan dan pengiraan sistem rancangan rawatan (TPS) serta ukuran filem radiokromik. Tambahan pula, data log daripada linac dianalisis untuk menyiasat ketidaktentuan mekanikal, termasuk prestasi pengkolimat berbilang daun dan membina peta fluens. Purata kadar perlepasan gama adalah 96.9 ± 1.3% untuk pengesan 2D, 99.2 ± 0.5% untuk data log dan 94.0 ± 3.1% untuk filem radiokromik pada kriteria gama 3% / 3 mm. Bagi 3% / 2 mm, kadar perlepasannya ialah 93.4 ± 2.6%, 98.7 ± 0.8% dan 86.2 ± 6.5%. Kadar perlepasan gama yang tinggi bagi pengesan PTW Octavius 1500 menunjukkan padanan yang kukuh dengan dos yang dirancang. Data log turut mengesahkan kebolehpercayaannya. Walaupun filem radiokromik yang digunakan sebagai piawaian emas untuk perbandingan dan menunjukkan kadar lulus yang lebih rendah, dan masih mengesahkan dos yang dihantar. Secara keseluruhan,

pengesan 2D adalah alat yang boleh dipercayai untuk mengesahkan rancangan rawatan kompleks dan memastikan penyampaian dos yang tepat, terutamanya dalam rancangan yang menyebentuk.

EVALUATION OF THE ACCURACY OF 2D DETECTOR ARRAY SYSTEM FOR PATIENT-SPECIFIC QUALITY ASSURANCE (PSQA) IN ADVANCED RADIOTHERAPY

ABSTRACT

Advanced radiotherapy techniques, such as volumetric-modulated radiotherapy (VMAT), deliver a highly conformal dose to the tumour target while minimising the dose to organs at risk (OAR). Patient-specific quality assurance (PSQA) plays a critical role in verifying the accuracy of the treatment plan delivery. However, the complexity of highly conformal plans can result in lower gamma passing rates and higher dosimetric error, particularly for smaller volume of OAR. This study evaluated the accuracy of the 2-dimensional (2D) detector array, PTW Octavius 1500 in PSQA for advanced radiotherapy by comparing its results with the absolute dose measurements and log data. Dose accuracy was assessed by the detector array measurements with treatment planning system (TPS) calculations and absolute dose from radiochromic film measurement. Additionally, log data from the linear accelerator (linac) were analysed to investigate mechanical uncertainties, including multileaf collimator (MLC) performance, and to reconstruct the fluence map. The average gamma passing rates were 96.9 ± 1.3% for detector array, 99.2 ± 0.5% for log data and 94.0 ± 3.1% for radiochromic film at 3% / 3 mm gamma criteria, while at 3% / 2 mm, the passing rates were 93.4 ± 2.6%, 98.7 ± 0.8%, and 86.2 ± 6.5%, respectively. The PTW Octavius 1500 detector showed high gamma passing rates, indicating strong agreement with planned doses. Log data further confirmed its reliability. While radiochromic film used as gold standard for comparison, showed slightly lower passing rates, it still validated the delivered dose. Overall, the detector array is a reliable tool for verifying complex

treatment plans and ensuring accurate dose delivery, especially in highly conformal plans.

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Radiotherapy plays a crucial role in the treatment of more than 50% of cancer patients, for both curative and palliative purposes (Atun et al., 2015; Zhang et al., 2022). It uses ionising radiation beams to kill cancerous cells, while sparing healthy normal cells (Sánchez-Nieto *et al.*, 2020). According to the International Atomic Energy Agency (IAEA), the cancer cure rate by radiotherapy alone or in combination with surgery or chemotherapy is up to 40% globally (Rosenblatt and Zubizarreta, 2017).

The radiotherapy process begins with patient imaging and simulation. A computed tomography (CT) scan is performed to capture the anatomical images of the patients which are then imported into the treatment planning system (TPS). The radiation oncologist contours the planning target volume (PTV) and organ at risk (OAR) to ensure precise treatment targeting. Once the target and critical structures are defined, the medical physicist utilises the TPS to develop an optimised treatment plan. This involves selecting appropriate beam angles, energy levels, field sizes and modulation techniques to achieve the best dose distribution. The plan is evaluated using Dose-Volume Histograms (DVH) to ensure that the tumour receives the prescribed radiation dose while limiting exposure to the surrounding healthy tissues. Once the plan is reviewed and approved, it is transferred to the linear accelerator (linac) for treatment delivery (Chaput and Regnier, 2021; Hansen et al., 2022). A linac is a high-energy x-ray machine that is used to deliver the prescribed radiation dose to the tumour inside the patient's body during radiotherapy treatment (Shamsi *et al*., 2018).

With the current advancements in radiotherapy technology and techniques, advanced radiotherapy, such as intensity-modulated radiotherapy (IMRT), volumetric-modulated radiotherapy (VMAT), stereotactic radiosurgery (SRS), and stereotactic body radiotherapy (SBRT), have been developed to enhance treatment precision. These techniques allow a higher radiation dose to be delivered to the PTV and further minimise the dose to the OAR (Abazarfard *et al.*, 2021). The dose conformality for advanced radiotherapy techniques is obtained via an inverse planning technique to determine the best treatment parameters to be delivered using conformal radiotherapy delivery technology (Abazarfard *et al.*, 2021; Zouiri *et al.*, 2021). However, these advancements increase the complexity of treatment planning and delivery (Behinaein *et al.*, 2019; Das *et al.*, 2021). The complexity level of the plan depends on the patient's anatomy, dose constraints and the dose calculation algorithm (Chiavassa *et al.*, 2019). Patient-specific quality assurance (PSQA) must be performed to ensure the prescribed treatment plan is being delivered accurately and within the acceptable tolerance before transferring the plan to the linac (Pal *et al.*, 2021).

According to the International Commission on Radiation Units (ICRU) Report 46, the error of the whole radiotherapy treatment process can be originated from contouring PTV and OAR, treatment planning and calculation, PSQA, patient positioning during radiotherapy treatment and dose delivery. The total errors should be less than 5% to achieve the treatment objective (International Commission on Radiation and Measurements (ICRU), 1992). Moreover, according to the Technical Report Series No. 430 (TRS 430), the maximum error in delivering radiation dose for the entire radiotherapy process needs to be less than ± 5% to achieve the treatment purpose. Besides, the treatment cure rate is reduced by 20% when there is a treatment error of

more than of ± 5% (International Atomic Energy Agency (IAEA), 2004). Therefore, PSQA is an important step before proceeding with the radiotherapy treatment to reduce the treatment error (Abazarfard *et al.*, 2021; Kolarevic *et al.*, 2022).

1.2 Problem Statement

PSQA is a process to verify the accuracy of the dose distribution calculated by the TPS (Kimura *et al.*, 2020; Pal *et al.*, 2021). According to the American Association of Physicists in Medicine (AAPM) Task Group 119 (TG-119), the gamma passing rate of 3% / 3 mm should achieve at least 95% during the PSQA process (Gary *et. al.*, 2009). However, the gamma passing rate for highly conformal IMRT case may be lower due to the complexity of the plan and higher dosimetric error for smaller volume of OAR (Stasinou *et al*., 2022) and it may not reflect the actual dose accuracy. This is due to the complexity of the plan where a higher degree of dose modulation is involved during planning process, leading to more uncertainties in the radiotherapy treatment delivery (Stasinou *et al*.,2022). The uncertainties included dose calculation uncertainty and mechanical uncertainty as mentioned by Park *et.al*. (2018). The dose calculation uncertainty increased with excessively modulated plan due to the frequent usage of the small or irregular shape beam apertures which is a limitation for the dose calculation algorithm. On the other hand, the complicated mechanical movement including the multileaf collimator (MLC), gantry rotation and beam delivery system of the excessive dose modulation plan also increased the mechanical uncertainty (Park et al., 2018). Besides, the dosimetric error in smaller volume of OAR also affects the gamma passing rate as a small discrepancy in the total dose in small volume of OAR during PSQA could lead a higher percentage difference in dosimetric error (Zheng *et al.*, 2021). Woon

et. al. (2018) also showed that the spatial resolution of the two-dimensional (2D) detector array was inadequate to detect the dose difference during PSQA in a high dose gradient region of the treatment field resulting in a lower gamma passing rate. As a result, gamma passing rate alone is not adequate to reflect the dose discrepancies during the PSQA process.

Radiochromic film can provide absolute dose measurement and is useful for assessing the accuracy of PSQA in advanced radiotherapy plan. The dose measured by the radiochromic film at the reference point and across the planar distribution can compare with the TPS calculated dose through point dose difference and gamma index analysis for radiotherapy treatment verification. Radiochromic film is ideal for PSQA in radiotherapy due to its submillimetre spatial resolution, water-equivalent composition and angular independence, providing precise and accurate dose verification (Santos et al., 2021). An anthropomorphic phantom is proposed to be used in this study as the phantom meets the requirement for accurate dose verification representing the variation of human tissue density and the peripheral region with a high dose gradient during PSQA (Kesavan *et al.*, 2022).

On the other hand, the log data for PSQA may provide additional measurements such as the linac's MLC performance (Midi and Zin, 2017). The log data acts as a supplementary method to perform PSQA as the data is obtained from the service graphing tool where no additional device is used during the process, thus, reducing the error during data acquisition process (Midi and Zin, 2017; Mubarok *et al.*, 2019). Study showed that the log data were able to detect the MLC deviation during radiation beam delivery. They also found significant correlation between the percentage of MLC

deviation throughout radiation beam delivery and gamma passing rate obtained from the 2D detector array (Yousif et al., 2023). Moreover, previous study showed that the MLC position error was within 3.5 mm when obtaining log data which was within the tolerance limit as recommended by the AAPM TG-142 (Mubarok *et al.*, 2019).

1.3 Study Objective

1.3.1 General Objective

The main aim of the research is to investigate the accuracy of 2D detector array system (PTW Octavius 1500 detector) for patient-specific quality assurance in advanced radiotherapy, using absolute dose measurement from radiochromic film and log data.

1.3.2 Specific Objectives

1. To measure the dosimetric accuracy of the PTW Octavius 1500 detector by validating relative dose measurements against dose calculations from the TPS.
2. To measure the absolute dose distribution from the radiochromic film in an anthropomorphic phantom and compare it with measurements obtained from the PTW Octavius 1500 detector.
3. To compare the accuracy of the treatment parameters delivery using log data.

1.4 Significance of the Study

This study is aimed to evaluate the accuracy of the 2D detector array measurement in detecting and quantifying clinically significant dose delivery errors such as MLC positional deviations and dose discrepancies in radiotherapy treatment. The PSQA is important for verifying that the planned dose can be accurately delivered to a phantom under treatment-like conditions. This process ensures the dose delivered to the target volume in clinical practice for the advanced radiotherapy technique such as VMAT closely match the planned dose with minimum treatment error to fulfil the treatment purpose. Besides, the study aimed to evaluate the accuracy and limitations of the high resolution 2D detector array by comparing its result with linac log data and radiochromic film. The findings from this study are expected to contribute to improved QA practices and help improve treatment safety and accuracy to the advanced radiotherapy.

1.5 Outline of the Study

Chapter 1 introduced the study by outlining the background and motivation behind the research, particularly the need for accurate and reliable PSQA methods in advanced radiotherapy techniques. The chapter also defined the scope of the study and presented the main research objectives, providing context for the evaluation of verification tools used in advanced radiotherapy techniques.

Chapter 2 presented a comprehensive literature review that contextualises the current study within existing research. It summarises key developments in 2D detector array systems, the application of radiochromic film in dosimetry, the growing use of

log files for dose reconstruction and the implementation of end-to-end verification strategies. The review identified knowledge gaps and justified the need for a comparative analysis of these verification methods.

Chapter 3 described the materials and methods employed in the study. This included detailed descriptions of the PTW Octavius 1500 detector array, the Max-HD head and neck anthropomorphic phantom, radiochromic film and the procedures for acquiring and analysing log data. The chapter also outlines the experimental setup, data acquisition protocols, film calibration procedures and analytical approaches used to evaluate the accuracy and reliability of each verification method.

Chapter 4 presented the results of the PSQA evaluations. It included quantitative comparisons of dose distributions obtained from the 2D detector array, radiochromic film and fluence map reconstructed from log data. The findings were categorised into absolute and relative dose verification and mechanical parameter accuracy.

Chapter 5 provided a critical discussion of the results, interpreting their clinical relevance and implications for routine PSQA practice. It also addressed the strengths and limitations of each verification method, as well as the challenges of implementing a multi-tool PSQA workflow in clinical settings. Suggestions for future research, such as the potential integration of Monte Carlo (MC) simulations and dose volume histogram (DVH)-based analyses were also discussed.

Chapter 6 concluded the thesis by summarising the key findings and contributions of the study. It highlighted the practical value of the PTW Octavius 1500 detector array,

the complementary role of radiochromic film and log file analysis and the importance of combining multiple verification tools to ensure accurate and robust PSQA in advanced radiotherapy.

CHAPTER 2

LITERATURE REVIEW

2.1 Advanced Radiotherapy

Radiotherapy is a cancer treatment modality that uses a linear accelerator (linac) to deliver a prescribed radiation dose directed towards the tumour within the patient body to deliver therapeutic dose that kill the cancerous cells (Sánchez-Nieto *et al.*, 2020). While effective, the treatment must be carefully administered, as the radiation beam affects both cancerous and heathy cells. With the current radiotherapy technology and techniques, advanced radiotherapy such as volumetric-modulated radiotherapy (VMAT), has been implemented to enhance the precision and accuracy of treatment planning and delivery of radiotherapy dose (Behinaein *et al.*, 2019; Das *et al.*, 2021). The advanced radiotherapy technique provides a higher radiation dose to the planning target volume (PTV) while further minimise the dose to the organ at risk (OAR) as compared to conventional three-dimensional conformal radiotherapy (3DCRT) (Abazarfard *et al.*, 2021).

2.1.1 Linear Accelerator (Linac)

Linac is made up of electron injection system, radiofrequency (RF) power generation system, accelerating waveguide, auxiliary system, beam transport system, beam collimation and beam monitoring system as shown in Figure 2.1 (Gibbons *et al.*, 2014; Podgorsak, 2014). Electrons are thermionically emitted from the electron gun in the injection system and accelerated to a desired kinetic energy in the accelerating waveguide (Podgorsak, 2014). The accelerated electrons were then passed through the beam transport system into the linac treatment head. The photon beam was produced

when the electrons hit the target inside the linac treatment head, meanwhile, the target was removed for the electron beam production (Gibbons *et al*., 2014). The produced radiation beam will be shaped by the MLC into regular or irregular field sizes based on the tumour shape in the beam collimation system (Sachse, 2017). The MLC was made of a high attenuating material such as tungsten alloy (atomic number = 74; density = 19.3 g/cm^3) that blocked the transmission of the primary radiation beam through the MLC according to the set field size opening. The primary radiation beam transmission through the leaves and interleaf were less than 2% and 3%, respectively when the radiation beam travelled through the MLC (Ohira *et al*., 2020; van Eeden *et al*., 2020). The dose rate, beam symmetry and flatness of the radiation beam were monitored by the ionisation chamber (IC) in the beam monitoring system before the radiation beam was delivered to the tumour during the radiotherapy treatment (Podgorsak, 2014).

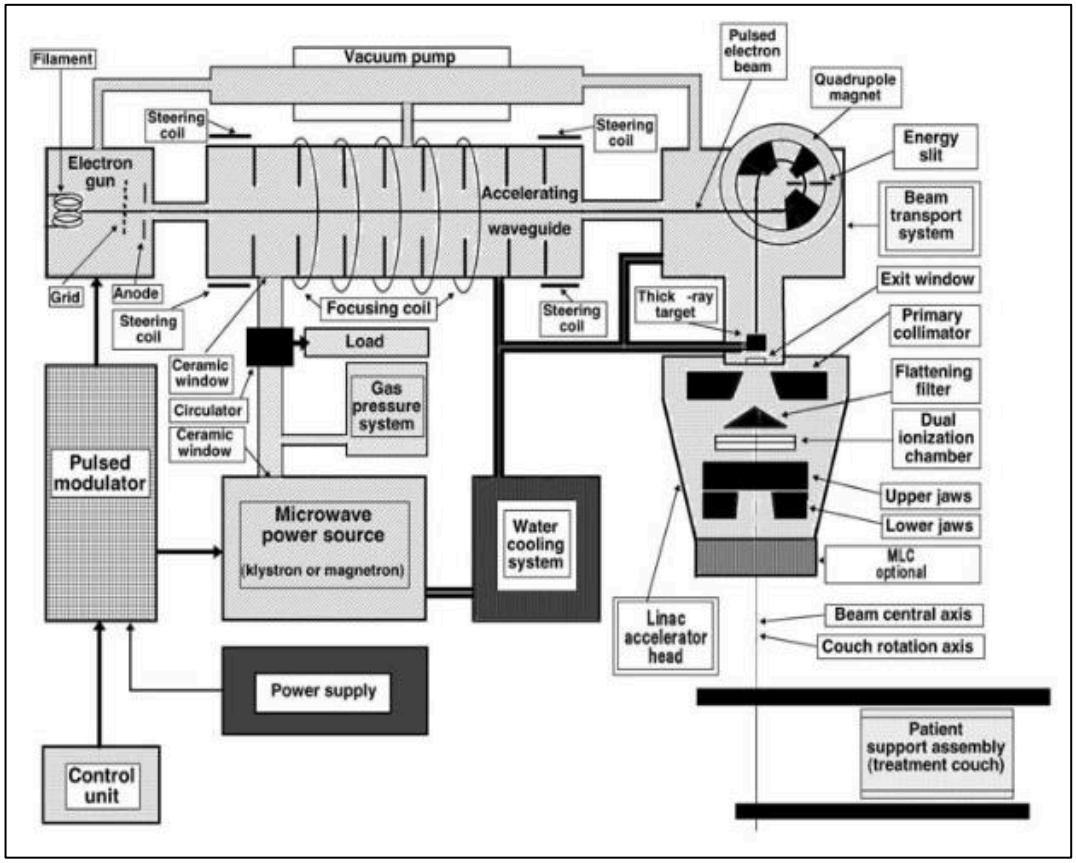

Figure 2.1: Schematic diagram of linac components including electron injection system, RF power generation system, accelerating waveguide, auxiliary system, beam transport system, beam collimation and beam monitoring system (Podgorsak, 2014).

2.1.2 Volumetric-Modulated Radiotherapy (VMAT)

Volumetric-modulated radiotherapy (VMAT) is an advanced radiotherapy techniques that utilised small field size beamlets in rotational treatment delivery (Behinaein *et. al.*, 2019). In the VMAT technique, the beam intensity modulation was achieved using small fields produced by the changing shape of MLC together with a simultaneous variation of the gantry rotation speed and changing of dose rate for each gantry angle during treatment delivery (Abazarfard, Azadeh & Mostaar, 2021; Zouiri *et. al,* 2021). The modulation of the beamlets provided a steep dose gradient which in turn created a high dose conformity and uniformity over target volume while limiting the radiation to the OAR and surrounding normal tissue (Khan and Gibbons, 2014; Onizuka, Araki & Ohno, 2018).

VMAT enables the delivery of highly conformal dose distributions and generally reduces treatment time and monitor unit (MU) compared to conventional IMRT techniques. The shorter treatment duration not only enhances patient comfort but also reduces the likelihood of intrafraction errors. Due to these advantages, VMAT has been rapidly adopted in clinical practice across numerous treatment centres (Masi et al., 2013).

The VMAT planning employs complex dose calculation algorithm (DCA) in treatment planning system (TPS) and the complexity of the modulated plan was depended on the patient's anatomy, dose constraints and optimisation algorithm

(Behinaein *et. al.*, 2019; Chiavassa, *et.al.*, 2019). The VMAT planning utilised an inverse planning system that adjusted the beam intensity and opening of MLC to find the best configuration for target volume irradiation and OAR sparing (Zouiri *et. al,* 2021).

2.1.3 Treatment Plan Complexity

In radiotherapy treatment planning, the complexity metrics were used to describe the degree of dose modulation. A higher degree of dose modulation indicates a more complex radiotherapy treatment plan. This often leads to an increase of uncertainty in dose delivery due to the limitation of linac components in dose modelling during treatment delivery (Crowe et al., 2014).

Complexity metrics can be categorised into fluence map-based metrics and aperture-based metrics. Fluence map-based metrics calculates the complexity of plan based on the resulting fluence of each pixel element from a given beam or plan. Meanwhile, the aperture-based metrics based on the variation of the MLC position and shape during treatment delivery to determine the plan complexity (Valdes et al., 2016).

Modulation complexity score (MCS) is an example of aperture-based complexity. It describes the distance travelled by leaf pairs in relation to the variation of aperture shape. The MCS expresses the treatment plan complexity in three parameters including segment shape, area and weight (Masi et al., 2013; McNiven et al., 2010; Sumida et al., 2017). It has a fixed range between 0 to 1 with the higher value of MCS indicates a lower complexity of the treatment plan (Hernandez et al., 2018).

The plan complexity can affect the dose delivery by the linac and affect the radiotherapy treatment verification. According to Jubbier et. al. (2021), the plan for head and neck (HN) site was more complicated than pelvis site with the MCS for HN and pelvis plan were 0.499 ± 0.116 and 0.643 ± 0.174, respectively. This was due to the HN case requiring more complex radiotherapy treatment plan to avoid surrounding OAR, ensuring the radiation dose was delivered to the PTV while minimising exposure towards the OAR as compared to the pelvis case (Jubbier et al., 2021). Moreover, Agnew et. al., (2014) found out that the MCS for HN plans were low (0.237 ± 0.067) due to the complexity of plan among all other treatment sites. Moreover, the mean MCS for HN sites were 0.383, 0.191 and 0.224 for studies conducted by Sumaida et. al. (2017), Viola et. al. (2022) and Rajasekaran et. al. (2015), respectively. These studies had showed that the HN plans had a lower MCS with higher plan complexity comparing to other treatment sites. These plans increased the uncertainty in dose delivery by the linac machine (Crowe et al., 2014). Based on Viola et. al. (2022), the optimal threshold for MCS was 0.142, whereby those treatment plans with MCS lower than 0.142 were considered as plans that had higher probability to fail the radiotherapy treatment verification PSQA and therefore, re-optimising the plans were needed.

2.2 Radiotherapy Treatment Verification

Radiotherapy treatment verification is essential to ensure the reliability of the treatment delivery and improved the patient safety for the whole radiotherapy treatment (Huang *et. al.*, 2021). According to TRS 430, there is a reduction of the treatment curability by around 20% when there were 5% sub-dosage of the tumour in the whole radiotherapy treatment course (IAEA, 2004). Moreover, the complexity of each individual TPS plan and complex movement of MLC during treatment delivery caused

discrepancies between the planned dose and delivered dose (Pal *et. al.*, 2021). To ensure the accuracy of each treatment plan, radiotherapy treatment verification must be done on individual-by-individual basis. Therefore, patient-specific quality assurance (PSQA) is essential before the delivery of advanced radiotherapy treatment to the patient as recommended by American Association of Physicists in Medicine Task Group 119 (AAPM TG-119) (Gary *et. al.*, 2009; Chiavassa, *et.al.*, 2019; Kimura *et. al.*, 2020; Kolarevic *et. al.*, 2022).

PSQA in radiotherapy treatment verification confirmed the dose computation accuracy of TPS for each plan that will be delivered by the linac (Kesavan, Senthilkumar & Hariprasanth, 2022). The dose is typically verified using a combination of a detector to measure the dose and a phantom to represent the patient. To provide a reference dose that will be compared to the measured dose, the dose planned to the patient is recalculated on a suitable phantom-detector combination. The dose delivered by the linac, is typically measured with film, IC or detector array in a phantom. The measured dose is compared with the dose distribution calculated by the TPS. This comparison was evaluated using an analysis method suitable to the measurement technique (Osman & Maalej, 2021). The dose distributions between the measured and the calculated reference dose are compared using gamma index analysis, dose difference analysis at specific points, along profiles and across 2D and 3D dose distribution as well as dose volume histogram (DVH) comparisons (Kimura *et. al.*, 2020).

In addition, the linac performance during treatment delivery can be assessed using log data as part of radiotherapy treatment verification. The log data-based

verification methods can provide the machine parameters such as MLC position accuracy and leaf speed deviations during delivery and can be used to reconstruct the delivered fluence. The delivered fluence can be analysed using gamma index analysis or fluence difference analysis, in addition to the accuracy of treatment parameters delivered by the linac (Mubarok et al., 2019).

2.2.1 Relative Dose Verification using 2D Detector Array

Relative dosimetry involves measuring radiation dose distributions relative to a reference or maximum point dose and expressed as a percentage rather than absolute units like Gray (Gy). Two-dimensional (2D) detector array is typically used for relative dosimetric verification in the clinical practice of PSQA. The detector array consists of hundreds to thousands of IC arranged in 2D arrays.

2D detector array can be used with the Octavius 4D phantom for 3D dose measurements during PSQA. The Octavius 4D phantom is a motorised cylindrical polystyrene phantom (Cilla et al., 2021). The polystyrene has tissue-equivalent density, to simulate dose delivery to human tissue during radiotherapy (Kesavan *et al.*, 2022). The detector rotates synchronously with the gantry of linac based on an inclinometer attached to the linac gantry. This ensure that the radiation beam is always perpendicular to the detector during the dose measurement, thus, reducing errors due to the directional dependence of the detector and allowing the 3D dose reconstruction (Agnew et al., 2014; Cilla et al., 2021; McCulloch et al., 2020).

The detector array is commonly used in PSQA due to its ability to measure dose profiles, planar dose distribution and reconstruct 3-dimensional (3D) dose distributions for radiotherapy treatment verification (Giordanengo and Palmans, 2018). The detector

array can provide dose measurements with near real-time acquisition and allows simultaneous collection of multiple point doses during the dosimetric verification (Hussein et al., 2013; Van Esch et al., 2014).

The 2D detector array is utilised as a relative dosimeter, where the measured dose values are normalised to a maximum point dose within the treatment field. This method evaluates the spatial accuracy of dose delivery by comparing the shape and distribution of the measured dose against that calculated by the TPS rather than the absolute dose values (Miften et al., 2018; Urso et al., 2018). The discrepancy between the measured and the calculated dose is evaluated using dose difference either point dose, dose profiles or planar dose distributions, as well as gamma index analysis using either global or local normalisation. Additionally, the measured dose distribution can be mapped onto patient's CT image from the TPS that enable DVH-based comparisons which further enhancing the clinical relevance of the verification process (Calvo-Ortega et al., 2014).

One of the limitations is the insufficient spatial resolution of detectors affects the accuracy of dose verification in regions with steep dose gradients such as OAR located nearby the target volume (Szczurek et al., 2019). Woon et. al. (2018) reported that the parotid for head and neck plans had the highest dosimetric errors as the parotid was anatomically closer to the target volume where the region had the steepest dose gradients. Besides, the lack of anatomical specificity of the detector array provides only a quantitative measure of dose deviation without indicating the anatomical location of failed points within the patient anatomy (Szczurek et al., 2019).

2.2.2 Absolute Dose Verification using Radiochromic Film

Absolute dosimetry involves directly measuring of radiation dose in Gy. Radiochromic film is used for absolute dosimetric verification in PSQA. The film consists of an active layer sandwiched between two 125 μm matte-polyester substrates as depicted in Figure 2.2. The film exhibited high spatial resolution. Its dose response is linear within range of 0.2 to 10 Gy, which aligns with therapeutic dose level used in IMRT, VMAT and brachytherapy (Palmer et al., 2015).

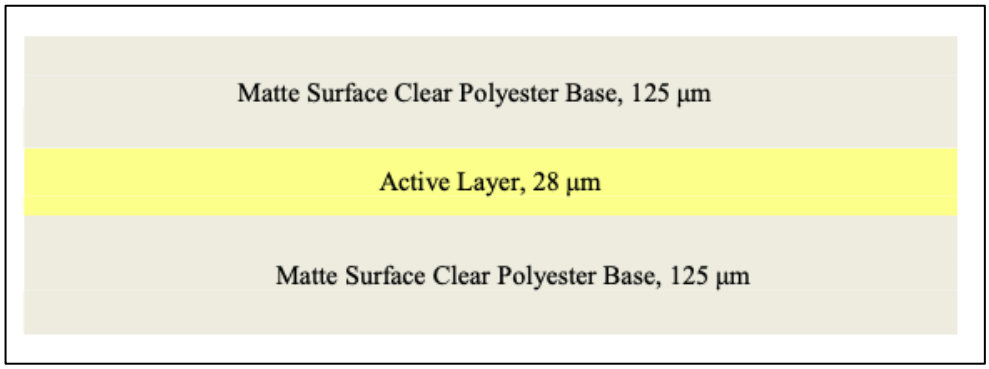

Figure 2.2: Structure of GAFChromic EBT3 dosimetry film.

Radiochromic film is utilised due to several advantages. It provides submillimetre spatial resolution, enabling precise dose measurements. Compared to 2D detector array, the film provides higher spatial resolution, allowing more prcecise dose variation detection, whereas the discrete detector spacing in 2D detector array can lead to a smoothing effect in steep dose gradient regions (Hussein et al., 2013). Study also reported that the angular dependence of radiochromic film response to be within 1% for photon beams, indicating a minimal variation in dose measurement with changing beam angles. Therefore, film can provide accurate measurements regardless of the angle of incident radiation. This supports its suitability for dose verification during gantry rotation and non-coplanar beam deliveries (Niroomand-Rad et al., 2020). These

characteristics make radiochromic film a valuable tool for dose verification in radiotherapy applications, particularly in advanced radiotherapy techniques where accurate verification of complex dose distributions, small field size and non-coplanar beam angles is essential to ensure treatment accuracy (Santos et al., 2021). However, there are several drawbacks, including the lack of immediate readout, non-reusability and cost (Mehrens et al., 2020).

Radiochromic film is calibrated to provide absolute dose in units of Gy. This enables a direct comparison with the planned dose distributions calculated from the TPS (Wen et al., 2016). Analytical methods applied to film-based verification include point dose analysis, dose profile comparison and 2D gamma index analysis (Santos et al., 2021).

Scanning of irradiated films requires careful handling to avoid misinterpretation and inaccurate results. Palmer et al. (2015) reported the film curvature on the scanner bed can introduce up to a 4% dose measurement error during scanning and recommend using a glass compression plate to mitigate this effect. Moreover, the lateral response artifact (LRA) occurs when scanning radiochromic film on a flatbed scanner, as variations in pixel values arise from film positioning relative to the scanner centre, where less light reaches the detector due to mirror reflectivity angles, causing higher optical density and dose deviations toward the scanning area edges (Lewis and Chan, 2015; Shameem et al., 2022). Besides, Wen et al. (2016) suggested that employing the red channel for low dose ranges (<10 Gy) and the green channel for high dose ranges yielded the most accurate results for PSQA on advanced radiotherapy.

2.2.3 End-to-end Dosimetry

End-to-end dosimetry is a QA process that evaluates the entire radiotherapy workflow, from CT simulation, contouring and treatment planning to dose verification using anthropomorphic phantom with film, patient positioning and dose delivery. This ensures that all components throughout the radiotherapy process function correctly and the delivery dose accurately matches the planned dose within acceptable tolerance, enhancing confidence in the system's ability to calculate and deliver the prescribed radiation dose (Bao et al., 2021; Saenz et al., 2016). End-to-end dosimetry is suitable for verifying the complete treatment chain in radiation oncology by mimicking the entire clinical workflow for a treatment course.

The end-to-end dosimetry often employs anthropomorphic phantoms that simulate patient anatomy and tissue heterogeneity, such a Computerised Imaging Reference Systems (CIRS) phantoms (head, thorax, pelvis) (CIRS, Norfolk, VA), Imaging and Radiation Oncology Core (IROC) phantom and Quasar Multi-Purpose phantom (Modus QA, London, Ontario, Canada). In some cases, institutions develop custom in-house water-equivalent phantoms for verification process (Kazantsev et al., 2020; Schreiner, 2019). The anthropomorphic phantom, designed to replicate anatomically accurate patient tissue heterogeneities, has been incorporated into the end-to-end dosimetry for radiotherapy treatment verification (Kazantsev et al., 2020; Loughery et al., 2019). Unlike the solid water phantom, the anthropomorphic phantom contains tissue-equivalent material that is closely resemble to actual human anatomy in both appearance and internal structure (Bao et al., 2021).

Radiation dose distribution depends on tissue density, as differences in electron density influence the attenuation, scattering and absorption of radiation beams. In low-density tissues such as the lung, radiation beams undergo less attenuation, leading to increased transmission and potential underdosing of the tumour. Conversely, in high-density tissues like bone, the beam is attenuated more significantly, potentially causing localised dose enhancements or perturbations. These interactions can introduce discrepancies between planned and delivered doses, especially in anatomically complex regions. Heterogeneous phantoms which incorporate materials that mimic the radiological properties of various tissues allow a more realistic evaluation of treatment beam delivery accuracy. By replicating the heterogeneity of patient anatomy, such phantoms enable end-to-end dosimetry to identify potential sources of error and verify the overall accuracy of the radiation therapy workflow (Yadav et al., 2023). Supporting this, Gurjar et al. (2015) reported the percentage dose difference between calculated and measured dose were found to be 2.36% and 3.31% for heterogeneous and homogeneous phantom, respectively, highlighting that higher discrepancies were observed with homogenous phantom.

Anthropomorphic phantoms can be tailored to accommodate various dosimetric detectors based on the specific goals of end-to-end dosimetry. For instance, phantoms with insert cavities can place IC for precise absolute dose verification at defined anatomical sites, such as the tumour site or OAR. Film-compatible phantoms allow placement of radiochromic film in coronal, sagittal or axial planes to capture high-resolution 2D dose distributions in anatomically relevant orientations. Phantoms designed with small cavities or detachable inserts can be used with point detectors such as thermoluminescent dosimeters (TLD) or optically stimulated luminescent dosimeters

(OSL), ideal for measuring localised point dose in critical structures (Miften et al., 2018). More advanced phantoms can accommodate 3D dosimetry systems such as PRESAGE or polymer gels, enabling full volumetric dose measurements with high spatial resolution (Zhu et al., 2023).

The radiochromic film can be used with the phantom during the radiotherapy treatment verification process. Geometric and material limitations of phantom can introduce inaccuracies in PSQA. The sharp edge of the square phantom caused perturbation in the dosimetric results by the films when there were an oblique irradiation field (Won et. al. 2018; Kesavan, Senthilkumar & Hariprasanth, 2022). Previous study found up to 8% dose difference when performing dose verification using sharp edge phantom (Won et al., 2018). Beyond geometric factor, the use of homogenous, non-anthropomorphic phantom can impact dose verification accuracy. Dunn et. al. (2015) pointed out that the TPS calculated dose distribution based on the patient-specific heterogeneity, therefore, using a homogeneous phantom may lead to dose discrepancies between the calculated and measured dose distribution (Dunn et al., 2015). Similarly, previous study argued that homogenous phantom was not ideal for evaluating complex radiotherapy treatment plans as the phantom failed to represent realistic patient anatomy and tissue composition (Dimitriadis et al., 2017).

2.3 Dose Analysis

Radiotherapy treatment verification is essential to ensure that the planned dose is accurately delivered to the patient, which is critical for both patient safety and treatment efficacy (Huang et al., 2021). After treatment delivery, various dose analysis methods are employed to assess the agreement between the calculated dose from the TPS and

the measured dose delivered by the linac to verify the accuracy and reliability of radiation treatment delivery.

Point dose analysis involves the measurement of the dose at a specific location within a phantom using IC or film. The measured dose is then compared to the dose calculated by the TPS at the same reference point (Low et al., 2018). Verification can be performed for either the target or OAR, depending on where the IC or film positioned within the phantom (Miften et al., 2018). A common guideline is that the range between the maximum and minimum doses across the IC or film should be within 5% of the mean dose (Miften et al., 2018). While this method is considered dependable and repeatable, particularly in areas with low dose gradients, it is limited in its ability to detect spatial errors or dose inconsistencies in high-gradient areas or across the entire treatment field. To ensure reliable results, the point dose analysis should be located in a region with uniform dose distribution (Miften et al., 2018). In clinical applications, the average percentage difference between the point dose measured by the IC and the TPS-calculated values was 1.51% for head and neck (HN) patients and 1.04% for brain patients, with standard deviations of 0.81% and 0.94%, respectively (Low et al., 2018). This approach is useful for verifying the treatment plan dose which is critical for assessing the accuracy of MU calculations by the TPS. A key limitation of single point dose analysis is that it only measure dose at a single point. Although this measured dose is compared with the treatment plan dose, it does not offer enough data to validate the overall accuracy of the plan. Besides, minor errors in positioning the IC or film during dose measurement can result in significant discrepancies between the measured dose and planned dose (Miften et al., 2018).

Planar dose analysis involves evaluating 2D dose distributions measured across a specific plane using detector such as 2D detector arrays or radiochromic film (Low et al., 2018). This method is employed to assess the 2D dose patterns of individual advanced radiotherapy fields, offering a relative comparison between measured data and the QA calculated plan. The TPS export the dose distributions at the same measurement plane, allowing dose distribution comparisons with the acquired data from the detector system (Miften et al., 2018). Analysis involves overlaying the measured and calculated dose distribution for visual inspection such as isodose lines or applying quantitative techniques like gamma index evaluation to assess agreement (Miften et al., 2018). Compared to point dose analysis, planar dose analysis offers a broader spatial assessment, making it well-suited for detecting spatial discrepancies in highly modulated fields. However, its sensitivity is limited to the measurement plane, making it less effective for detecting errors that occur outside the geometry.

3D dose analysis is an advanced method of evaluating the accuracy of delivered dose distributions in advanced radiotherapy. Unlike point or planar dose analysis, 3D dose analysis allows for volumetric comparison of planned and delivered dose distributions, providing a more clinically relevant assessment of potential discrepancies (Low et al., 2018). Some available detector arrays have been developed for 3D dose analysis. Systems like PTW Octavius 4D system (PTW, Freiburg, Germany) and Sun Nuclear ArcCHECK (Sun Nuclear, Florida, US) utilise 2D detector arrangements in cylindrical or rotating geometries to reconstruct dose distributions in 3D from measured dose throughout the treatment delivery. These systems often combine measured data with treatment plan information to reconstruct the dose in a phantom or patient geometry using software-based interpolation or algorithms. These systems offer

practical, efficient and clinically feasible alternatives for routine patient-specific QA, with reasonably high spatial resolution and reproducibility (Miften et al., 2018).

Gamma index analysis can be conducted on planar dose distributions as well as on 3D dose distribution (Miften et al., 2018). Gamma index analysis evaluates the performance of the TPS to ensure the planned dose accurately reflects the dose delivered to the patient. The gamma index analysis combines dose difference (DD) and distance to agreement (DTA), providing a more comprehensive assessment than dose analysis alone, which does not account for errors in dose accuracy relative to its spatial location (Liura and Pawiro, 2020). The gamma passing rate is the percentage of points that achieve the condition where the gamma index is lower than one (Querebalú Garcia et al., 2021). The tolerance for gamma index analysis of 3% DD and 3 mm DTA should be achieve 95% passing rate as recommended by AAPM TG-119 (Gary *et. al.*, 2009).

DD is the percentage difference between the measured dose from dosimeter and the calculated dose from TPS. DTA is known as the distance between the point of measured dose and the nearest point of the calculated dose that are having the same absorbed dose (Mohamed et al., 2018). In principle, both acceptance criteria were evaluated independently whereby DD is applied in low dose gradient region while DTA is applied in high dose gradient region (Querebalú Garcia et al., 2021). However, Low et. al. (1998) included both criteria during gamma index analysis.

The ellipsoid surface in Figure 2.3 represents the acceptance criterion. The surface is given by an equation:

$$\gamma(r_m) = \sqrt{\frac{|r_m - r_c|^2}{(\Delta DTA)^2} + \frac{|D_m(r_m) - D_c(r_c)|^2}{(\Delta DD)^2}} \qquad \text{(Eq. 2.1)}$$